SEDIMENT TRANSPORT APPENDIX

1   SEDIMENT TRANSPORT PROCESSES

1.1   General

The sediment cycle begins with the erosion of soil and rock in a watershed and transport of that material by surface runoff. The transport of sediment through a river system consists of multiple erosional and depositional cycles, as well as progressive physical breakdown of the material. Many sediment particles are intermittently stored in alluvial deposits along the channel margin or floodplain, and ultimately re-entrained via bank and bed erosion. Total sediment loads consist of suspended load (the fine-grained fraction transported in the water column) and bedload (the coarse-grained fraction transported along the channel bed). The transport of sediment through the stream system depends on the sediment supply (size and quantity) and the ability of the stream to transport that sediment supply.

1.2   Sediment Transport Processes and Aquatic Habitat

The caliber, volume, and transport dynamics of sediment exerts a major control on channel form and geomorphic processes that create and sustain aquatic habitat in all river systems. Sediment caliber dictates what geomorphic features and associated habitat types (e.g., sand bed vs. gravel bed) will be characteristic of a given channel. Sediment volume can affect the stability of a channel, causing channel aggradation if the volume delivered is in excess of the transport energy available, and causing channel degradation if the volume is insufficient. Sediment volume may also affect channel pattern and slope, with high volumes of coarse sediment resulting in relatively steep slopes, high width/depth ratios, and braided channel patterns.

Some degree of sediment mobility is critical for the ecological health of a stream system. Booth and Jackson note that anadromous salmonids "depend on particular combination of water and sediment fluxes to maintain favorable channel conditions." Most Pacific Northwest aquatic organisms have evolved within dynamic stream systems, in which pools, bars, and other habitat features are continually reworked and reformed. Physical habitat is created and sustained through processes such as the maintenance of pools and riffles, the formation of transient bars, side channels, and backwater areas, the deposition of spawning gravels, and the flushing of fines from bed substrate.

Sediment sorting through selective transport creates spawning habitat and quality habitat for benthic organisms, which in turn are food for aquatic species such as fish. The maintenance of pool-riffle sequence morphologies and the effective sorting of bed materials exemplify balanced conditions of sediment caliber and transport energy that serve to generate and maintain quality aquatic habitat.

1.3 Sediment Transport and Stream Morphology

1.3.1 General

Sediment transport and storage count among the major interdependent variables that determine stream morphology. Many channel features, including depositional bars, riffles, and dunes are manifestations of sediment transport and storage. Table X lists typical features and associated sediment transport characteristics for the seven basic channel types defined by Montgomery and Buffington[3]. Although a number of channel classification schemes exist, that of Montgomery and Buffington serves well for the purpose of examining the role of sediment transport in determining stream morphology.

As seen in Table X, the characteristic features of various channel types are often, to a great degree, the product of the balance between sediment supply and transport. For instance, cascade and step pool channel morphology is maintained by the stability of large, relatively immobile bed materials[4]. Smaller bed material readily moves through these channels during lesser flow events. Such channels are considered to be in a sediment supply-limited state (the capacity of the channel for sediment transport exceeds the sediment inputs). In contrast, dune ripple channel morphology is indicative of a sediment transport-limited situation, in which the sediment supply exceeds the ability of the channel to transport sediment. Significant bed load transport occurs in dune ripple channels over a broad range of discharges, including relatively low flows. Plane bed and pool riffle morphologies include a mix of transport- and supply-limited characteristics, with the presence of depositional bars in pool riffle systems suggesting a tendency towards transport-limited conditions[5]. Channel bars represent temporary sediment storage in the stream channel, and also represent the incipient floodplain that may become established if additional sediment is deposited on the bar and vegetation takes hold. Bedrock channels tend to be supply-limited, and alluvial materials tend to occur only in "shielded" areas such as scour holes and behind obstructions. Colluvial channels are strongly influenced by hillslope processes, and the majority of long-term sediment flux from these channels appears to be the result of debris flows[5].

Table X. Channel types, characteristic features, and corresponding sediment transport processes based on Montgomery and Buffington[5]

Channel Type	Characteristic Features	Corresponding Sediment Transport Processes
Cascade	• "Disorganized" bed material typically consisting of cobbles and boulders • Small, irregularly spaced pools less than a channel width apart	• Large, bed-forming materials typically become mobile only in large flood events (i.e., 50-100 yr events) • Gravel stored in low energy sites is transported by lesser floods • Sediment conditions are probably supply-limited
Step Pool	• Discrete steps formed by large-diameter material separating pools containing finer materials • Pool lengths generally equal 1-4 channel widths	• Like cascade channels, large, bed-forming materials typically become mobile only in large flood events • Gravel stored in low energy sites is transported during lesser floods • Sediment transport is probably supply-limited
Plane Bed	• Characterized by long stretches of	• Seem to be a transitional state between sediment supply- and

	featureless bed • Composed of sand to boulder sized materials (typically gravel to cobble)	sediment transport-limited channel form
Pool Riffle	• Contain alternating topographic depressions (pools) and high points (bars and riffles) typically spaced 5-7 channel widths apart • Generally unconfined, with well-developed floodplains • Generally occur at moderate to low gradients • Substrate varies from sand to cobble (typically gravel)	• Display both sediment supply- and sediment transport-limited characteristics, but the presence of depositional bar forms suggest that they are more transport-limited than plane bed channels
Dune Ripple	• Typically low gradient, sand bed channels containing relatively mobile dunes, bedload sheets, and ripples	• Sediment transport-limited
Bedrock	• Bedrock bed • Often, some alluvial material stored in scour holes and behind obstructions	• Generally reflect a high transport capacity relative to sediment supply
Colluvial	• Small headwater streams founded on colluvial fill	• Weak or ephemeral fluvial transport • Long-term sediment flux from these channels appears to be dominated by debris-flows

1.3.2 Effects of Large Woody Debris on Sediment Transport

Large woody debris in streams increases hydraulic complexity, influencing the local velocity fluctuations that determine the scour and deposition of sediment, and because of its form roughness is extremely important for energy dissipation. In general, the presence of woody debris tends to increase the sediment storage capacity of a reach. Other effects of large woody debris include sorting of sediment sizes, inducing bar formation, inducing local scour, and causing sediment deposition in channels and on floodplains that provides for riparian vegetation colonization and forest flood plain development[3,5,6,7,8]. Woody debris can actually "force" pool riffle and step pool channels by inducing the formation of pools, bars, and steps[3,8]. In extreme cases, log jams may force the presence of alluvial beds in otherwise bedrock reaches[3]. Woody debris jams play a major role in sediment transport dynamics, as water and sediment stored behind jams can be rapidly released, creating transport events ranging from small sediment pulses to high magnitude debris flows and floods. (DW's response)

1.3.3 Effects of Dams and Weirs on Sediment Transport

The trapping of sediment behind dams and weirs (e.g., in sediment detention basins) often results in the release of sediment-deficient water from the structure. In effect, as long as a weir or dam acts as a sediment trap, it produces a "decoupling of the sediment transport conveyor belt."[9] As a result of the decreased sediment load, erosion and armoring (hardening of bed with immobile, large substrate) of the channel bed downstream of dam or weir often occurs, as smaller-sized materials are winnowed from the bed and are not replaced.[9,10,11] Below large dams, this bed immobility is further accentuated by the controlled release of water, which mutes peak flows[9]. Bed armoring can be preceded by incision if the

size and gradation of the native bed material is small relative to hydraulic forces (i.e., if a great deal of fine material is winnowed out in the armoring process). Such incision is more likely in pool riffle, plain bed, and dune ripple reaches, where bed materials are more readily transported under average to moderately high discharges, than in steeper step pool and cascade reaches where the key bed elements are stable at relatively high discharges.

1.3.3.1   Sediment Transport Analysis

1.3.3.1.1 General

Sediment transport is one of the most important, but least evaluated components of natural stream channel design in bedrock dominated channels, alluvial channels, colluvial channels, and wood-controlled channels alike. As a design component, sediment transport analyses focus on providing for sediment continuity, a factor that authors unanimously cite as a condition for true channel stability.[12,13,14,15] Channel stability in this context implies that there is no aggradation or degradation of the channel bed, or more simply, that the volume of material moving in equals the volume of material moving out.[14]

Sediment transport analysis poses many challenges. Most sediment transport analyses and design methods focus on channel competence, or the capacity of a channel to transport bed material of a given size.   Just as important as competence, but less frequently addressed, is consideration of the volume of sediment that a channel is capable of transporting. Measurement and prediction of sediment mobility and transport volumes are notoriously difficult and, in most cases, relatively inaccurate.[48]   Our ability to accurately characterize and predict sediment transport phenomena is growing every year. Still, model results tend to be more reliable when comparing "before" and "after" conditions rather than in determining absolute values. For this reason, analysis results should, in general, be used comparatively rather than absolutely. A number of currently accepted sediment transport analysis approaches and techniques are presented below.

1.3.3.1.2 The Type of Sediment in Transport

Sediment transport evaluations generally begin with a determination of the size fractions of sediment present within a given reach of channel. The measurement of sediment caliber can be performed by several methods including pebble counts, sieve analyses, or suspended sediment measurements. The most commonly used method of sampling coarse riverbed material is that developed by Wolman.[16] Despite the development of more sophisticated statistical techniques for bed material analysis, the pebble count method remains widely used due to its simplicity and almost universal acceptance.[17] Pebble counts are based on analysis of the relative area covered by given sizes, and essentially consist of measuring the intermediate axis of 100 clasts collected either at random or within a grid. This sample represents the armor layer, and the resulting particle size distribution may be coarser than the average bed material distribution.

In cases where the dominant bed material is sand or finer, sieve analysis is necessary. Sieve analysis is conducted on bulk samples taken from the field, and consists of sifting sediment through several standard sized sieves.[18] The amount of sediment remaining on each sieve is then weighed to determine the percent of the total weight of a given size fraction. When the material is finer yet, suspended sediment measurements are necessary. Suspended sediment measurement is usually done by pipette analysis.[19] Sediment sampling allows for estimation of size gradations in motion at given flows and provides useful information on design elements relative to substrate size.

1.3.3.1.3 The Mobility of Bed Sediment

Sediment in fluvial systems tends to move in a series of slugs, pulses, or waves (Figure G1).[20,43] For example, in a study on the East Fork River in Wyoming, Meade[21] concluded that sediment moved in three pulses over a one-year period. The movement of each pulse was correlated with the pulse of water discharge resulting from snowmelt. This study also suggested that sediment is transported downstream in a series of waves; when discharge increases, material stored in pools moves to the next pool downstream. Such wave-like or pulse-like movement is typical of semi-arid streams (or streams with coarse bed load), though it may be less common in humid environments.[20]

Placeholder - Insert a Paragraph about sediment mobility in stream morphologies dominated by wood. Sediment mobility is related to failures of wood structure, and pulses can be exaggerated.

1.3.3.1.4 Incipient Mobility of Sediment

The assessment of sediment mobility within a channel requires an understanding of the sediment size gradation present, as well as the transport energy available to mobilize that gradation. In many cases, the evaluation of the transport energy available to transport the size fraction present is deemed sufficient for channel design.[22] This is referred to as "incipient mobility", and addresses mobility purely in terms of sediment size mobilized, rather than sediment volume mobilized. In more complex cases, however, such as those in which the incoming sediment volumes are either excessively large or small, the more difficult calculation of transport volumes may be necessary. Sediment volume is typically represented by stream power, which represents the force needed to transport sediment in a channel. Stream power is a representation of channel capacity, or the quantity of material that the flow is able to transport. A thorough review of various stream power equations is provided by Rhoades.[23]

The coarse fraction of a given sediment gradation is generally not in motion under low flow conditions. As flow increases, the energy imparted on sediment increases until at some point, the particle is mobilized. The point at which a sediment particle is just set into motion is referred to as incipient motion, and the shear stress at incipient motion is called the critical shear stress.

Shear stress is a measure of the erosive force acting on the channel boundary, with the force acting parallel to the area. In a channel, shear stress is created by water flowing parallel to the boundaries of the channel. Shear stress can be divided into bed shear and bank shear. Bank shear can be determined

by multiplying the bed shear value by a coefficient from Lane.[12] Maximum bank shear, based on a trapezoidal channel, is approximately 0.75 times the bed shear at a distance 1/3 up from the channel bed. Different channel shapes and bends will also affect the values for bank shear.

Shear stress calculations determine the force of the water on the channel particles. By knowing the amount of shear stress in a stream, the particle size necessary to withstand these forces can be found. This is important when designing a channel to withstand a certain design flow or flood flow. Shear is calculated by the equation,

$$\tau = \gamma R s$$

where τ is the shear stress, γ is the specific weight of water (specific weight of water is inversely related to water temperature), R is the hydraulic radius (R = cross-sectional area of flow divided by the wetted perimeter), and s is the slope of the channel. For wide shallow channels with width/depth ratios of 12 or higher, channel depth can be substituted in place of hydraulic radius to simplify the equation shown above. Shear stress is commonly expressed in units of pounds per square feet (psf). The water depth is a function of flow magnitude and channel geometry. Shear stress will therefore be greatest in steep streams during high flows.

Critical shear is the shear stress required to mobilize sediment of a particular grain size. In order to calculate critical shear stress, the Shields equation is used:

$$\tau_c = \tau_c^* (\gamma_s - \gamma) D$$

where τ_c^* is the dimensionless Shields parameter for entrainment of a sediment particle of size D, and γ_s and γ are the unit weights of sediment and water, respectively, expressed in pounds per cubic foot.[20] Generally, the parameter D is taken to be D_{50}, the median grain size of the bed sediment. The Shields parameter is dependent on particle size and packing, and may range from 0.1 for loosely packed gravel to 0.01 for imbricated deposits (imbricated deposits have been arranged in a shingled fashion by streamflows and are particularly difficult to mobilize).[24] Incipient mobility of stream sediments has been actively researched for over 80 years, and a summary of this research can be found in Buffington and Montgomery.[25] Their work suggests that the lack of universal Shields parameter values warrants great care in selecting those values in mobility assessments.

In incipient mobility assessments, the critical shear value is generally calculated using the D_{50} of the sediment gradation present.[26] The use of the D_{50} to characterize the bed material size in mobility analysis is based on the hypothesis of equal mobility.[38] Originally proposed by Parker et al.[44], this hypothesis assumes that the "*bed-load* size distribution is approximated by that of the *substrate* for all flows capable of mobilizing most available gravel sizes"[38] (emphasis added). Although a number of authors have argued that bed-load size characteristics change in a phased or continuous manner in relation to discharge, the equal mobility hypothesis is still widely used in incipient motion analysis.[45,46,47]

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This is probably due to the added level of complexity, and perhaps uncertainty, involved in analyses that
allow for bed-load size characteristics to vary with discharge.

Sediment mobility has been described in terms of shear stress ratio, which (adopting the equal mobility
hypothesis) is the ratio of the shear stress present to the critical shear required to mobilize the D_{50}.
Wilcock and MacArdell[27] estimated that a shear stress ratio of 2 is needed to mobilize the entire bed of
a channel (although this depends to some extent on the particle size distribution). Channel stability was
defined by a bankfull shear stress ratio of 1 in the assessment procedure developed by Johnson et al.[24]
This implies that under conditions of sediment transport equilibrium, the median grain size is at incipient
mobility at bankfull discharge. Furthermore, at a bankfull shear stress ratio of greater than one, the
channel is likely to degrade; if the ratio is less than one, transport is limited and aggradation is likely. For
many channel designs, incipient motion for the D_{84} at bankfull is used for the design parameter. Only
moving the D_{50} results in channels that aggrade over time .

1.3.3.1.5 Channel Competence-Based Methods of Sediment Transport Analysis

Incipient motion analyses can be used to assess channel competence and to design channel components
(including habitat structures) to be stable under a given discharge. USDOT[15] and U.S. Army Corps of
Engineers[14] are useful references for utilizing tractive force (shear stress) analysis for design. Shear
stress is not, however, a practical measure of tractive force in steeper channels.[28]

1.3.3.1.5.1 Tractive Force Analysis

Analysis of tractive force, a generalized measure of shear stress, can be used to determine channel
geometry (considering primarily depth) based on the mobility of bed sediment.[30] Using this approach,
incipient motion analysis as described in "Incipient Mobility of Sediment" (above) is used to assess the
mobility of the stream bed and bank materials. Because the theoretical mobile particle size is calculated,
the tractive force method can be used to design a channel that is essentially rigid (non-erodible) at the
design discharge.[15] Tractive force analyses can also be used to design channel components, such as
banks, to withstand the shear forces associated with a given design discharge.[15] USDOT[15] includes
information on the calculation of shear in channel bends and on the shear resistance of various materials
commonly used in channel design. Alternatively, if a mobile channel bed is desired, tractive force
analysis can be applied to determine a fraction of the bed material that is mobile at a given design
discharge. Two methods for addressing mobile channel beds in design are addressed below.

1.3.3.1.5.2 Mobile Channel Bed Under Fixed Slope Conditions

This approach can be applied when slope is fixed due to vertical constraints as well as lateral floodplain
constraints. Analysis of moving (or 'live') beds with a known or constrained slope most often makes
use of extremal hypotheses.[26] Extremal hypotheses state that a stable channel will adopt dimensions that
lead to minimization and maximization of certain parameters. For instance, extremal hypotheses include
the minimization of stream power, maximization of sediment transport, minimization of stream power per
unit bed area, minimization of Froude number, and the maximization of friction factor. These hypotheses
and their application to river design are summarized in Chang[26]. Chang[26] combined several of the

extremal hypotheses, along with standard hydraulic analysis, to generate a numerical model of flow and sediment transport, the FLUVIAL 12 model. The model was used to make repeated computations of channel geometry with various values for input variables. Results of the analysis were used to construct a family of design curves that yield channel depth and width when given discharge, slope, and bed material size.

1.3.3.1.5.3   Mobile Channel Bed Under Known Sediment Concentration

Using this approach, design will ensure that the sediment entering the reach is transported out of the reach by manipulating channel dimensions. Upstream stable channel dimensions can be used to calculate an assumed sediment supply. Channel designs will be iterated such that the channel dimensions are all capable of transporting the incoming sediment load. Because many combinations of channel dimensions will be able to do this, a family of slope-width or slope-depth relations are the end result of this type of analysis. The designer then selects any combination of channel properties that are represented by a point on the curves. Selection may be based on minimum stream power, maximum possible slope, width constraint due to right-of-way, or maximum allowable depth. The hydraulic design package 'SAM' performs this series of analyses for sand bed channels and is available for public use.[29]

1.3.3.1.6 Limitations of Competence-Based Methods

Sediment size and incipient motion particle size are relatively easy to characterize from deposited bed sediments and hydraulic analysis (see the discussion of "tractive force" above). As mentioned previously , however, ediment volume is much more difficult to quantify. Sediment volume is typically calculated using sediment transport equations, which are notoriously inaccurate.[30,31] There are numerous sediment transport equations, each of which was developed for specific types of conditions and purposes. As such, they are only applicable to specific types of channels.

Modeling of sediment transport remains one of the central thrusts of fluvial geomorphic and hydraulic research. It is likely that quantification of sediment volume will eventually become a routine part of channel design once the limitations of sampling and characterization are reduced. Presently, however, the scope of most project design efforts does not include an analysis of sediment transport volume, and quantifying sediment transport remains one of the greatest challenges of, and limitations to, river channel design.

1.3.3.2 Sediment Transport Equations and Models

There are numerous sediment transport equations, each of which was developed for specific types of conditions and purposes. Table G1 lists a number of transport equations and the slope and sediment sizes for which they were developed. The applicability of most of the equations is related to the local bed particle size.   Whenever possible, the use of measured sediment loads for testing and calibration of the chosen equation(s) is preferred (actual equations and detailed descriptions are available in standard sediment transport texts, e.g., Chang)[26]

Table G1. Commonly used transport equations and the conditions for which they were developed

Author	Year	Slope Range	Sediment Size	Data Source
Meyer-Peter Muller	1948			
Toffaleti	1968			
Yang				
Yang				
Parker				
Yang				
Yang				
Ackers and White				
Engelund and Hanson				
Laursen				

In addition to the specific sediment transport equations, there are several sediment transport numerical models available for use in river engineering applications. The most common approach to sediment transport modeling is a steady-state, one-dimensional approach. That is, using channel dimensions, flow conditions, and sediment characteristics, the model performs hydraulic calculations, and then using these hydraulic characteristics, calculates sediment loads for each of the channel reaches. Based on the quantity of sediment transported for the given flow, the channel elevation (i.e., slope) is adjusted via a routing scheme. The program either performs calculations for a given range of flows, or for a given flow, the model continues until there are no more channel adjustments (i.e., equilibrium conditions). This modeling approach is the basis for the Corps of Engineers HEC-6 model, and is widely used.[42]

Placeholder: The primary limitation of the HEC-6 approach is that it is a one-dimensional model: no changes are allowed in the width dimension.

The next level of modeling is the semi two-dimensional modeling approach. In two-dimensional models, a similar coupled hydraulic and sediment routing scheme is used, but at the end of the routing run an estimate is made as to whether or not channel width adjustments are appropriate. Several methods are used to estimate stable channel widths: extremal hypotheses as described earlier (GSTARS 2.0, FLUVIAL 12)[26], or bank stability estimated from stable slope angles (GSTARS 2.0, CONCEPTS)[26]. These models add a significant feature of width adjustment without adding significantly to data or analysis efforts needed. In all, these are felt to be the most appropriate approaches for most river restoration designs, particularly those projects that will involve significant modification to channel

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alignment, slope, or sediment loads.

The third level of modeling is the fully two-dimensional or three-dimensional modeling approaches. These models represent significant improvements in describing fluvial erosion and hydraulic processes, but this comes at a significant increase in the level of effort needed both in terms of data and analysis requirements beyond current capability. In fact, while utilization of 2-D modeling is beginning to become more widespread for large projects, practical application of 3-D modeling continues to be impractical due to technological limits such as computer capabilities and high input requirements.

1.3.3.3 Sediment Storage

It is important for the channel designer to consider accommodating sediment storage within reaches. Designing a channel that transports all sediment inputs in a natural manner will, theoretically, prevent channel destabilization by excessive erosion or deposition. It does not, however, guarantee that the geomorphic and habitat benefits of sediment storage (e.g., as gravel bars) will be realized. On reaches where some degree of sediment storage is desired and appropriate, channel dimensions and plan form should be varied to encourage and accommodate depositional features such as bars.

The appropriate volume/extent of sediment storage is best determined using an analog (reference) reach. Natural channels typically contain reaches characterized by deposition, transport, or relatively balanced sediment transport. Factors such as channel gradient, valley width, and woody debris presence/density in particular influence sediment storage on any given reach. Channel designers should take these factors into account and intentionally make provisions for sediment storage on reaches where such storage is appropriate.

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